FILTERED CALCULATION OF SENSOR ARRAY INDUCED PHASE ANGLE INDEPENDENT FROM DEMODULATION PHASE OFFSET OF PHASE GENERATED CARRIER

CROSS-REFERENCE TO RELATED APPLICATION

This application contains subject matter that is related to the subject matter of the following application, which is assigned to the same assignee as this application. The below-listed application is hereby incorporated herein by reference in its entirety:

"CALCULATION OF SENSOR ARRAY INDUCED PHASE ANGLE INDEPENDENT FROM DEMODULATION PHASE OFFSET OF PHASE GENERATED CARRIER," by David B. Hall, Serial No. _________, filed June 20, 2003.

STATEMENT OF GOVERNMENT RIGHTS

The Government of the United States of America has rights in this invention pursuant to Contract No. N00024-02-C-6305 awarded by the U.S. Department of the Navy.

TECHNICAL FIELD

The invention relates generally to signal processing and more particularly to demodulation of signals from fiber optic sensor arrays.

BACKGROUND

Fiber optic sensor arrays of a time division multiplexed ("TDM") system are often used to measure a change in a parameter, for example, acoustic vibration, fluid pressure variations, acceleration, and magnetic field intensity. The fiber optic sensor array employs a phase generated carrier with a period T to measure the change in the parameter at a given sampling rate. The fiber optic sensor array converts a phase angle associated with the parameter to an amplitude variation on an output pulse of light.

The phase angle is measured through various demodulation techniques of the output pulse. Typical demodulation techniques employ a quadrature component Q and an in-phase component I of the output pulse. The quadrature component Q corresponds to a sine of the phase angle, and the in-phase component I corresponds to a cosine of the phase angle. An arctangent of the ratio Q/I is equal to the phase angle. The magnitude of the change in the parameter can then be calculated from the change in the phase angle.

Calculation of the quadrature component Q and the in-phase component I requires multiple samples of the output pulse at specific intervals of the phase generated carrier. The output pulse is filtered to improve characteristics of the output pulse. A period of the phase generated carrier is significantly longer than a period of the output pulse. The longer period of the phase generated carrier requires the samples to span several output pulses to obtain each required interval of the phase generated carrier. The longer period of the phase generated carrier reduces the sampling rate of the demodulation technique.

High-speed phase generated carriers (e.g., a frequency greater than 1MHz, or a period less than 1000 nanoseconds) do not permit the precise control of a demodulation phase offset β associated with the phase generated carrier. One shortcoming of the demodulation techniques is that a variation in the demodulation phase offset β from a fixed value reduces the accuracy of the demodulation techniques.

Thus, a need exists for reduced dependency on demodulation phase offsets for demodulation techniques of fiber optic sensor arrays that employ phase generated carriers and filters.

SUMMARY

The invention in one embodiment encompasses a method. A sensor array employs a parameter to induce a time-varying phase angle φ on an optical signal that comprises a phase

generated carrier with a demodulation phase offset β. An output signal from the sensor array is filtered to create a filtered signal. The phase angle φ is calculated independently of the demodulation phase offset β through employment of the filtered signal.

Another embodiment of the invention encompasses an apparatus. A sensor array employs a parameter to induce a time-varying phase angle φ on an optical signal that comprises a phase generated carrier with a demodulation phase offset β. The apparatus comprises a filter component that filters an output signal from the sensor array to create a filtered signal. The apparatus further comprises a processor component that employs the filtered signal to calculate the phase angle φ independent from the demodulation phase offset β.

A further embodiment of the invention encompasses an article. A sensor array employs a parameter to induce a time-varying phase angle φ on an optical signal that comprises a phase generated carrier with a demodulation phase offset β. The article includes one or more computer-readable signal-bearing media. The article includes means in the one or more media for filtering an output signal from the sensor array to create a filtered signal. The article includes means in the one or more media for calculating the phase angle φ independently of the demodulation phase offset β through employment of the filtered signal.

DESCRIPTION OF THE DRAWINGS

Features of exemplary implementations of the invention will become apparent from the description, the claims, and the accompanying drawings in which:

FIG. 1 is a representation of one exemplary implementation of an apparatus that comprises one or more lasers, one or more optical switches, one or more phase modulators, one or more sensor arrays, one or more optical receivers, one or more filter components, and

one or more processor components for calculating a phase angle of an optical signal independently of a demodulation phase offset.

FIG. 2 is a representation of an exemplary plot of one or more interference pulses for the exemplary implementation of FIG. 1.

FIG. 3 is a representation of one exemplary set of calculations for the exemplary implementation of FIG. 1.

FIG. 4 is a representation of another exemplary set of calculations for the exemplary implementation of FIG. 1.

FIG. 5 is a representation of an amplitude response of a fourth order Bessel low-pass filter as an exemplary filter component of the apparatus of FIG. 1

FIG. 6 is a representation of an impulse response of the exemplary implementation of FIG. 1 with the exemplary filter component of FIG. 5.

FIG. 7 is a representation of an exemplary input signal to and the respective output signal from the filter component of FIG. 5.

FIG. 8 is an enlarged view of the output signal of FIG. 7.

FIG. 9 is an exemplary filtered signal from the filter component of FIG. 5 of an exemplary phase generated carrier and the output signal of FIG. 7.

FIG. 10 is an exemplary ratio R_s of the filter component of FIG. 5 as a function of the demodulation phase offset.

FIG. 11 is an exemplary ratio R_s of the filter component of FIG. 5 as a function of a modulation depth.

FIG. 12 is a plot of a peak value of an exemplary quadrature term and a peak value of an exemplary in-phase term from the filter component of FIG. 5 as a function of the demodulation phase offset.

FIG. 13 is a plot of an exemplary accuracy $\Delta\varphi$ of the calculation of the phase angle by the apparatus of FIG. 1 with the filter component of FIG. 5 as a function of the demodulation phase offset.

FIG. 14 is a plot of an exemplary accuracy $\Delta\varphi$ of the calculation of the phase angle by the apparatus of FIG. 1 with the filter component of FIG. 5 as a function of a phase angle φ.

DETAILED DESCRIPTION

Turning to FIG. 1, an apparatus 100 in one example comprises a plurality of components such as computer software and/or hardware components. A number of such components can be combined or divided in the apparatus 100. An exemplary component of the apparatus 100 employs and/or comprises a set and/or series of computer instructions written in or implemented with any of a number of programming languages, as will be appreciated by those skilled in the art.

Referring to FIG. 1, the apparatus 100 in one example comprises one or more lasers 102, one or more optical switches 104, one or more phase modulators 106, one or more sensor arrays 108, one or more optical receivers 110, one or more filter components 111, and one or more processor components 112. In one example, the apparatus 100 demodulates an optical signal to measure a change in a parameter, as described herein. The laser 102 in one example comprises a continuous wave laser. The laser 102 generates and sends an optical signal through the optical switch 104 and the phase modulator 106 to the sensor array 108.

The optical switch 104 in one example comprises a time division multiplexed ("TDM") switch. The optical switch 104 gates the optical signal such that the optical signal

comprises a stream of optical pulses. The phase modulator 106 impresses a phase generated carrier ("PGC") 114 on the stream of optical pulses. For example, the laser 102, the optical switch 104, and the phase modulator 106 cooperate to create one or more optical pulses 116 that comprise the phase generated carrier 114, as will be understood by those skilled in the art. The optical pulse 116 comprises a period T_{pulse}. The period T_{pulse} in one example is approximately between 100 nanoseconds and 1000 nanoseconds. The phase generated carrier 114 in one example comprises a period T_{pgc} and a modulation depth of M. The period T_{pgc} comprises a relationship with a frequency $f_{pgc} = 1 / T_{pgc}$, as will be understood by those skilled in the art. The frequency f_{pgc} in one example is approximately between 2 MHz and 20 MHz. The phase generated carrier 114 is associated with a demodulation phase offset β. The phase generated carrier 114 creates a time-varying phase angle equal to

$$M \cdot \sin\left(\frac{2\pi \cdot t}{T_{pgc}} + \beta\right).$$

The sensor array 108 in one example comprises one or more sensors 124, 126, and 128, for example, mismatched path interferometers. The sensor array 108 splits the optical pulse 116 into one or more optical pulses 118, 120, and 122, for example, one pulse per sensor. The optical pulses 116, 118, 120, and 122 in one example are substantially the same. The sensors 124, 126, and 128 of the sensor array 108 receive the optical pulses 118, 120, and 122, respectively. The sensors 124, 126, and 128 of the sensor array 108 in one example employ one or more parameters and the optical pulses 118, 120, and 122 to create one or more respective interference pulses 130, 132, and 134. Exemplary parameters comprise acoustic vibration, fluid pressure variations, acceleration, and magnetic field intensity. For example, the sensor 124 splits the optical pulse 118 into a first portion and a second portion. The sensor 124 employs the parameter to induce a time-varying phase angle φ on the first portion of the optical pulse 118, relative to the second portion of the optical pulse 118. The

sensor 124 recombines the first portion of the optical pulse 118 with the second portion of the optical pulse 124 to create the interference pulse 130. A time-varying amplitude variation of the interference pulse 130 represents the time-varying phase angle φ between the first portion and the second portion of the optical pulse 118.

The optical pulses 116 comprise an intermediary spacing such that the interference pulses 130, 132, and 134 comprise a relatively small spacing, for example, a high duty cycle, as described herein. The interference pulses 130, 132, and 134 comprise a period substantially equal to the period T_{pulse} of the optical pulse 116. The sensor array 108 sends the interference pulses 130, 132, and 134 to the optical receiver 110 in a pulse train 136, for example, in a serial fashion. For example, the optical pulse train 136 comprises the interference pulses 130, 132, and 134.

The optical receiver 110 in one example comprises one or more photodiodes 138. In a further example, the optical receiver 110 comprises a transimpedance amplifier 140. The optical receiver 110 in one example comprises a polarization diversity receiver system (not shown), as defined in U.S. Patent No. 5,852,507, assigned to the assignee of the present invention. The optical receiver 110 receives the optical pulse train 136. The optical receiver 110 then creates one or more respective analog electrical signals that represent the interference pulses 130, 132, and 134 from the optical pulse train 136. For example, the optical receiver 110 converts a magnitude of power of the optical pulse train 136 to a voltage signal.

The filter component 111 in one example comprises a fourth order Bessel low-pass filter. In another example, the filter component 111 comprises a fourth order real pole filter. For example, the filter component 111 comprises a three decibel roll-off frequency between 10 MHz and 60 MHz. The three decibel roll-off frequency of the filter component 111 in one example is equal to 53 MHz. The filter component serves to filter the optical signal to create

a filtered signal. The filter component 111 in one example filters the analog electrical signals from the optical receiver 110 to create one or more filtered signals. For example, the filtered signals represent the interference signals 130, 132, and 134.

The processor component 112 in one example comprises a digital signal processor. In a further example, the processor component 112 comprises an analog-to-digital converter component 142. The processor component 112 in one example comprises an instance of a computer-readable signal-bearing media 144, as described herein. The analog-to-digital converter component 142 converts the filtered signal from the optical receiver 110 into a digital signal. The processor component 112 in one example serves to sense a change in the parameters by employing the time-varying amplitude variation of the interference pulses 130, 132, and 134 to calculate the time-varying phase angle φ.

An illustrative description of exemplary operation of the apparatus 100 is presented, for explanatory purposes. The laser 102, the optical switch 104, and the phase modulator 106 cooperate to create the one or more optical pulses 116. The sensor array 108 splits the optical pulse 116 into the optical pulses 118, 120, and 122. The sensors 124, 126, and 128 employ the parameters and the optical pulses 118, 120, and 122 to create the interference pulses 130, 132, and 134. The sensor array 108 sends the interference pulses 130, 132, and 134 as the optical pulse train 136 to the optical receiver 110.

The optical receiver 110 creates an analog electrical signal that represent the one or more interference pulses 130, 132, and 134. For example, the analog electrical signal is defined as $s(t, M, \beta, \varphi)$:

$$s(t,M,\beta,\varphi) = A + B \cdot \cos\left(M \cdot \sin\left(\frac{2\pi \cdot t}{T_{pgc}} + \beta \right) + \varphi \right),$$

where A is an average signal level, B is an interference term signal level, M is the modulation depth, T_{pgc} is the period of the phase generated carrier, β is the demodulation

phase offset, and φ is the phase angle. The phase angle of $s(t, M, \beta, \varphi)$ comprises a first portion due to the phase generated carrier, $M \cdot \sin\left(\frac{2\pi \cdot t}{T_{pgc}} + \beta\right)$, and a second portion due to the parameter, φ, as will be understood by those skilled in the art.

The filter component 111 filters the analog electrical signal to create a filtered signal. The analog-to-digital converter component 142 in one example converts the filtered signal into a digital signal that represents the interference pulse 130. The processor component 112 obtains a plurality of samples S_n, $n = 0$ to x, of the interference pulse 130 from the digital signal. The processor component 112 obtains the plurality of samples S_n at time intervals Δt over a period T_s. The period T_s in one example is substantially equal to the period T_{pgc} of the phase generated carrier 114. The period T_s in one example serves to promote an increase in sampling rate, as will be appreciated by those skilled in the art. The period T_s in one example is less than or equal to T_{pulse}.

The time interval Δt in one example is equal to an even fraction of the period T_{pgc}, (e.g. $T_{pgc}/8$ or $T_{pgc}/16$). In one example, the processor component 112 obtains the plurality of samples S_n starting at a time t_0, with a time interval Δt of $T_{pgc}/8$. For example, the plurality of samples S_n comprise eight samples at t_0, $t_0 + \Delta t$, $t_0 + 2\Delta t$, $t_0 + 3\Delta t$, $t_0 + 4\Delta t$, $t_0 + 5\Delta t$, $t_0 + 6\Delta t$, and $t_0 + 7\Delta t$. In another example, the processor component 112 obtains the plurality of samples S_n starting at a time t_0 with a time interval Δt of $T_{pgc}/16$. For example, the plurality of samples S_n comprise sixteen samples at t_0, $t_0 + \Delta t$, $t_0 + 2\Delta t$, $t_0 + 3\Delta t$, $t_0 + 4\Delta t$, $t_0 + 5\Delta t$, $t_0 + 6\Delta t$, $t_0 + 7\Delta t$, $t_0 + 8\Delta t$, $t_0 + 9\Delta t$, $t_0 + 10\Delta t$, $t_0 + 11\Delta t$, $t_0 + 12\Delta t$, $t_0 + 13\Delta t$, $t_0 + 14\Delta t$, and $t_0 + 15\Delta t$.

The processor component 112 employs one or more of the plurality of samples S_n to calculate one or more quadrature terms and one or more in-phase terms. The processor

component 112 in one example calculates a set of quadrature terms Q_j, $j = 0$ to y. For example, the set of quadrature terms Q_j comprises a number of quadrature terms equal to ½ a number of samples of the plurality of samples S_n. In one example where the plurality of samples S_n comprises eight samples, y is equal to three, and the processor component 112 calculates the set of quadrature terms Q_j as:

$$Q_0 = S_0 - S_4,\ Q_1 = S_1 - S_5,\ Q_2 = S_2 - S_6, \text{ and } Q_3 = S_3 - S_7 \text{ (FIG. 3).}$$

In another example where the plurality of samples S_n comprises sixteen samples, y is equal to seven, and the processor component 112 calculates the set of quadrature terms Q_j as:

$$Q_0 = S_0 - S_8,\ Q_1 = S_1 - S_9,\ Q_2 = S_2 - S_{10},\ Q_3 = S_3 - S_{11},$$

$$Q_4 = S_4 - S_{12},\ Q_5 = S_5 - S_{13},\ Q_6 = S_6 - S_{14}, \text{ and } Q_7 = S_7 - S_{15} \text{ (FIG. 4).}$$

The processor component 112 in one example calculates a set of in-phase terms I_k, $k = 0$ to z. For example, the set of in-phase terms I_k comprises a number of in-phase terms equal to ¼ the number of samples of the plurality of samples S_n. In one example where the plurality of samples S_n comprises eight samples, z is equal to one, and the processor component 112 calculates the set of in-phase terms I_k as:

$$I_0 = (S_0 + S_4) - (S_2 + S_6), \text{ and}$$

$$I_1 = (S_1 + S_5) - (S_3 + S_7) \text{ (FIG. 3).}$$

In another example where the plurality of samples S_n comprises sixteen samples, z is equal to three, and the processor component 112 calculates the set of in-phase terms I_k as:

$$I_0 = (S_0 + S_8) - (S_4 + S_{12}),\ I_1 = (S_1 + S_9) - (S_5 + S_{13}),$$

$$I_2 = (S_2 + S_{10}) - (S_6 + S_{14}), \text{ and } I_3 = (S_3 + S_{11}) - (S_7 + S_{15}) \text{ (FIG. 4).}$$

The processor component 112 employs the set of quadrature terms Q_j to calculate a quadrature term Q_s. The processor component 112 in one example calculates the quadrature term Q_s as:

$$Q_s = \sqrt{\sum_{j=0}^{j=y} Q_j^2} .$$

The quadrature term Q_s is independent of the demodulation phase offset β, as will be appreciated by those skilled in the art.

The processor component 112 employs the set of in-phase terms I_k to calculate an in-phase term I_s. The processor component 112 calculates a constant C_1 as described herein. The processor component 112 in one example calculates the in-phase term I_s as:

$$I_s = C_1 \times \sqrt{\sum_{k=0}^{k=z} I_k^2} .$$

The in-phase term I_s is independent of the demodulation phase offset β, as will be appreciated by those skilled in the art. The processor component 112 in one example calculates the constant C_1 such that respective maximum absolute values of the quadrature term Q_s and the in-phase term I_s are substantially equal at a modulation depth M of an operating range.

The modulation depth M in one example is between 1.0 and 1.7 radians. For example, the modulation depth M is sufficiently large to promote an increase in signal strength of the phase generated carrier 114. The modulation depth M in a further example is sufficiently small to promote stability of the quadrature term Q_s and the in-phase term I_s with respect to a change in the modulation depth M. For example, the modulation depth M is approximately equal to $\pi/2$.

The processor component 112 employs one or more of the set of quadrature terms Q_j and the quadrature term Q_s to calculate a quadrature term Q. The processor component 112 in one example employs a magnitude of the quadrature term Q_s and a sign of one of the quadrature terms of the set of quadrature terms Q_j to calculate Q. For example, the processor component 112 chooses the quadrature term Q_1 that comprises a relatively large magnitude to avoid a zero crossing of the magnitude. The processor component 112 chooses a different

quadrature term with a larger magnitude, for example, the quadrature term Q_0, when the magnitude of the quadrature term Q_1 approaches zero. The quadrature term Q is independent from the demodulation phase offset β, as will be appreciated by those skilled in the art.

The processor component 112 employs one or more of the set of in-phase terms I_k and the in-phase term I_s to calculate an in-phase term I. The processor component 112 in one example employs a magnitude of the in-phase term I_s and a sign of one of the in-phase terms of the set of in-phase terms I_s to calculate I. For example, the processor component 112 chooses an in-phase term I_l that comprises a relatively large magnitude to avoid a zero crossing of the magnitude. The processor component 112 chooses a different in-phase term, for example, the in-phase term I_0, when the magnitude of the in-phase term I_l approaches zero. The in-phase term I is independent from the demodulation phase offset β, as will be appreciated by those skilled in the art.

A change in the demodulation phase offset β in one example changes the sign of the quadrature term Q and/or the in-phase term I. Four bands of operation of width $\pi/2$ in one example exist across a total range of 0 to 2π for the demodulation phase offset β. Where the magnitude of the demodulation phase offset β is near a border of a band of operation, the magnitude of the in-phase term I_k chosen to determine the sign of I and/or the magnitude of the quadrature term Q_j chosen to determine the sign of Q may approach zero. When the magnitude of the in-phase term I_k chosen to determine the sign of I and/or the magnitude of the quadrature term Q_j chosen to determine the sign of Q approaches zero, the processor component 112 chooses a different quadrature term Q_j and/or in-phase term I_k. The processor component 112 chooses a different quadrature term Q_j and/or in-phase term I_k to promote the calculation of the phase angle φ independent from the demodulation phase offset β. The phase modulator 106 in one example maintains the demodulation phase offset β within a

range significantly smaller than $\pi/2$, therefore the demodulation phase offset β does not need to be known, as will be appreciated by those skilled in the art.

The processor component 112 employs the quadrature term Q and the in-phase term I to calculate the phase angle φ independently of the demodulation phase offset β. Since the quadrature term Q and the in-phase term I are independent from the demodulation phase offset β, the calculation of the phase angle φ is independent from the demodulation phase offset β. The processor component 112 in one example calculates the phase angle:

$$\varphi = \text{arctangent}\,(Q / I).$$

The processor component 112 in one example employs the change in the phase angle φ between multiple instances of the interference pulses 130, 132, and 134 to determine the change in the parameters employed by the sensors 124, 126, and 128.

Turning to FIG. 2, the plot 202 comprises an exemplary representation of the interference pulses 130, 132, and 134 and appropriate sampling times for the processor component 112 with respect to time t. The interference pulses 130, 132, and 134 are represented by the analog electrical signal $s(t, M, \beta, \varphi)$. The quadrature and in-phase components of the interference pulses are represented by $s(t, M, \beta, \pi/2)$ and $s(t, M, \beta, 0)$, respectively. One or more square pulses 230, 232, and 234 represent the period T_{pulse} of the interference pulses 130, 132, and 134, respectively. The square pulses 230, 232, and 234 comprise a spacing period of T_{space}. The square pulses 230, 232, and 234 in one example comprise a high duty cycle, for example, the sampling period T_s is substantially longer than the spacing period T_{space}.

The processor component 112 in one example obtains eight samples from the respective interference pulses 130, 132, and 134. The processor component 112 in one example obtains the samples at a constant rate over the period T_s. For example, the processor component 112 obtains eight samples, S_0 through S_7, for the interference pulse 130, discards

the next three samples $S_{discard}$, obtains the next eight samples, S_0 through S_7, for the interference pulse 132, discards the next three samples $S_{discard}$, and so forth.

Turning to FIG. 3, a plot 302 comprises a representation of a set of calculations for the quadrature terms Q_j and the in-phase terms I_k for eight samples of the interference pulse 130. Where eight samples are taken, x = 7, y = 3 and z = 1. The processor component 112 calculates a given term by adding and subtracting a plurality of the samples S_n in a respective row of the given term. The processor component 112 adds or subtracts a sample according to a sign designated in the row/column pair for the given term and the sample. If a sign is not listed for a sample, the sample is not used for the given term. For example, the processor component 112 calculates Q_0 as $+S_0 - S_4$, Q_2 as $+S_2 - S_6$, and I_0 as $+S_0 - S_2 + S_4 - S_6$.

Turning to FIG. 4, a plot 402 comprises a representation of a set of calculations for the quadrature terms Q_j and the in-phase terms I_k for sixteen samples of the interference pulse 130. Where sixteen samples are taken, x = 15, y = 7, and z = 3. For example, the processor component 112 calculates Q_0 as $+S_0$-S_8, Q_1 as $+S_2$-S_9, and I_0 as $+S_0$-S_4+S_8-S_{12}. Turning to FIGS. 3 and 4, patterns of the + and the – signs in one example can be seen for the quadrature terms Q_j and the in-phase terms I_k, respectively. For example, similar patterns can be used to calculate a set of quadrature terms Q_j and I_k for a plurality of samples with a different number of samples.

Turning to FIGS. 5-14, plots 502, 602, 702, 802, 902, 1002, 1102, 1202, 1302, and 1402 represent exemplary characteristics of the filter component 111, where the filter component 111 comprises a fourth order Bessel low-pass filter, and exemplary accuracy plots of the calculation of the phase angle φ by the apparatus of FIG. 1. The plots 502, 602, 702, 802, 902, 1002, 1102, 1202, 1302, and 1402 were generated using MathCAD (Mathsoft Engineering & Education, Inc., Cambridge, MA 02142, http://www.mathcad.com). Plot 502 represents an amplitude response $S_b(f)$ of an exemplary fourth order Bessel low-pass filter.

Plot 602 represents an impulse response b(t) of the exemplary filter component 111 of FIG. 4. Plot 702 represents an exemplary input signal env(t) to and the respective output signal ENV(t) from the filter component 111 of FIG. 4. Plot 802 represents an enlarged view of the output signal ENV(t) of plot 702. Plot 902 represents an exemplary filtered signal S(t) of an exemplary phase generated carrier 114 with the output signal ENV(t) of plot 702. Plot 1002 represents an exemplary ratio R_s as a function of the demodulation phase offset β. Plot 1102 represents the ratio R_s of plot 1002 as a function of the modulation depth M. Plot 1202 represents a peak value of an exemplary quadrature term Q_0 and a peak value of an exemplary in-phase term I_1 as a function of the demodulation phase offset β. Plot 1302 represents an exemplary accuracy $\Delta\varphi$ of the calculation of the phase angle φ as a function of the demodulation phase offset β. Plot 1402 represents an exemplary accuracy $\Delta\varphi$ of the calculation of the phase angle φ as a function of the phase angle φ.

Referring to FIG. 5, plot 502 comprises an exemplary amplitude response $S_B(f)$ for the filter component 111. A complex frequency response B(f) of the filter component 111, where the filter component 111 comprises a fourth order Bessel low-pass filter, is equal to:

$$B(f)=\frac{105}{\left[\left(\frac{f}{f_0}\right)^4-45\cdot\left(\frac{f}{f_0}\right)^2+105\right]+1i\cdot\left[105\cdot\left(\frac{f}{f_0}\right)-10\cdot\left(\frac{f}{f_0}\right)^3\right]}.$$

The three decibel roll-off of the filter component 111 is equal to $2.114f_0$.

Referring to FIG. 6, plot 602 comprises an impulse response b(t) of the filter component 111. The impulse response b(t) is equal to the Fourier transform of the frequency response B(f) of the filter component 111. The impulse response b(t) is equal to:

$$b(t)=\int_{-1E9}^{1E9} B(f)\cdot e^{2\pi\cdot 1i\cdot t}\,df.$$

Plot 602 comprises a real part Re(b(t)) and an imaginary part Im(b(t)), multiplied by 1000, of the impulse response b(t). Plot 602 further comprises a multiple of 10 times the real part Re(b(t)) to highlight the ripples on a trailing edge of the real part Re(b(t)). The imaginary part Im(b(t)) is equal to zero, so the impulse function b(t) is real.

Referring to FIG. 7, plot 702 comprises an exemplary input signal env(t) to the filter component 111. For example, the input signal env(t) represents the electrical signal from the photodetector 110 that represents the output signal 130. The output signal 130 in one example is a flat-top pulse of width 90 nanoseconds with rise and fall times of one nanosecond. The input signal env(t) is approximated by a super-gaussian envelope function as:

$$\mathrm{env}(t) = \exp\left(-\left(\frac{t-\tau_0}{T}\right)^{108}\right).$$

The filter component 111 creates the filtered signal that comprises a convolution ENV(t) of the input signal env(t) with the impulse function b(t). An impulse function bfit(t) is used to approximate the impulse function b(t) to speed up the calculation of ENV(t). The convolution ENV(t) is equal to:

$$\mathrm{ENV}(t) = \int_0^t \mathrm{bfit}(t-v)\cdot \mathrm{env}(v)\cdot dv.$$

The convolution ENV(t) comprises ripples at a leading edge and a trailing edge.

Referring to FIG. 8, plot 802 comprises highlights of ripples at the leading edge and the trailing edge of the convolution ENV(t) of plot 702. As can be seen, the convolution ENV(t) has a flat zone approximately between 30 nanoseconds to 90 nanoseconds. The processor component 112 takes the plurality of samples S_n from within the flat zone.

Referring to FIG. 9, plot 902 comprises a filtered output S(t) of the phase generated carrier 114 with the convolution ENV(t). The phase generated carrier 114 is created by the phase modulator 106 and is represented by s(t, M, β, φ):

$$s(t, M, \beta, \phi) = A + B \cdot \cos(\phi + M \cdot \sin(\frac{2\pi}{T_{pgc}} \cdot t + \beta)),$$

where A is an average signal level and B is an interference term signal level. For example, A = 1.2, B = 1.0, M = 1.5. The value of β is arbitrary, but is equal to 1.0 radian in FIG. 9. The phase generated carrier 114 is superimposed on the input signal env(t). The filtered output S(t) is equal to the convolution of the product of the input signal env(t) and s(t) with the impulse function bfit(t):

$$S(t, M, \beta, \phi) = \int_0^t bfit(t - v) \cdot env(v) \cdot s(v, M, \beta, \phi) \cdot dv.$$

Two values of φ are used to show quadrature and in-phase components of the filtered output S(t, M, β, φ). For example, φ is equal to 0 for the in-phase component, and φ is equal to π/2 for the quadrature component. The in-phase term component has a 2^{nd} harmonic frequency of 40MHz, with a period of 25 nanoseconds. The quadrature component has a fundamental frequency of 20MHz, with a period of 50 nanoseconds. The processor component 112 obtains the plurality of samples S_n over the period of 50 nanoseconds and within the flat zone of the convolution ENV(t). For example, where x=7, the processor component 112 takes eight samples at 6.25 nanosecond intervals. A first sample and a last sample of the eight samples are 43.75 nanoseconds apart. The processor component 112 takes the first sample between 29 nanoseconds and 45 nanoseconds to obtain the plurality of samples S_n within the flat zone.

Referring to FIG. 10, plot 1002 comprises a ratio R_s as a function of the demodulation phase offset β where the modulation depth M = 1.5. The ratio R_s is equal to:

$$R_s(M,\beta) = \frac{Q_s(M,\beta,\frac{\pi}{2})}{I_s(M,\beta,0)}.$$

For a modulation depth $M = 1.5$, the constant C_1 is approximately equal to 1.944. The ratio R_s is calculated when Q_s and I_s are at a peak value. The peak value of Q_s is at $\varphi = \pi/2$. The peak value of I_s is at $\varphi = 0$. FIG. 10 shows R_s where $M = 1.5$ and β between $-\pi$ and $+\pi$. A variation from a ratio of unity for R_s is approximately $\pm 0.1\%$.

Referring to FIG. 11, plot 1102 comprises the ratio R_s as a function of the modulation depth M for two values of the demodulation phase offset β. FIG. 11 shows that changes in β for a given value of M do not significantly change the ratio R_s.

Referring to FIG. 12, plot 1202 comprises a peak value of the quadrature term Q_0 and a peak value of the in-phase term I_1 as a function of the demodulation phase offset β. The processor component 112 calculates the sign of the quadrature term Q by employing one quadrature term of the set of quadrature terms Q_j, for example, Q_0. The quadrature term Q_0 is proportional to the sine of the phase angle φ. The processor component 112 calculates the sign of the in-phase term I by employing one in-phase term of the set of in-phase terms I_s, for example, I_1. The in-phase term I_1 is proportional to the cosine of the phase angle φ. A peak value for Q_0 where $\varphi = \pi/2$ and a peak value for I_1 where $\varphi = 0$ are plotted as a function of phase offset β in FIG. 12. Four zones in β of width $\pi/2$ where the sign of Q_0 and the sign of I_1 do not change are designated where I_1 crosses 0. The processor component 112 calculates the sign of Q and the sign of I based on the value of β for Q_0 and I_1. For example, where β is between approximately 1.1 and 2.6, both Q_0 and I_1 are positive, so $Q = +Q_s$ and $I = +I_s$.

Referring to FIG. 13, plot 1302 comprises an error $\Delta\varphi(M, \beta, \varphi)$ of the calculation of the phase angle φ as a function of the demodulation phase offset β for various values of the modulation depth M. The error $\Delta\varphi(M, \beta, \varphi)$ is equal to:

$$\Delta\phi(\mathrm{M},\beta,\phi) = \arctan\left(\frac{\mathrm{Q}(\mathrm{M},\beta,\phi)}{\mathrm{I}(\mathrm{M},\beta,\phi)}\right) - \phi.$$

Where the measured output phase angle arctan(Q / I) is equal to the input phase angle φ, the error $\Delta\varphi$ is equal to 0 and the accuracy of the calculation is maximized. FIG. 13 shows plots of $\Delta\varphi(M, \beta, \varphi)$ for M = 1.48, M = 1.50, and M = 1.52, where $\varphi = 1$. The accuracy $\Delta\varphi$ is within ±1 milliradian for β between 1.1 and 2.6 radians where M = 1.50. Where M = 1.48, the accuracy $\Delta\varphi$ is approximately 7 milliradians. Where M deviates from 1.50 by 20 milliradians, for example, M = 1.52 or M = 1.48, the accuracy $\Delta\varphi$ is approximately 7 milliradians.

Referring to FIG. 14, plot 1402 comprises the error $\Delta\varphi(M, \beta, \varphi)$ as a function of phase angle φ where the modulation depth M = 1.5 and three values of the demodulation phase offset β are within the zone from 1.1 to 2.6. Where β = 1.2, 1.7, and 2.4, the accuracy $\Delta\varphi(M, \beta, \varphi)$ is within ±1.0 milliradian. Referring to FIGS. 13 and 14, variations in the demodulation phase offset β do not significantly affect the accuracy $\Delta\varphi(M, \beta, \varphi)$ of the calculation of the phase angle φ.

The apparatus 100 in one example employs one or more computer-readable signal-bearing media. One example of a computer-readable signal-bearing media for the apparatus 100 comprises the recordable data storage media 144 of the processor component 112. For example, the computer-readable signal-bearing media for the apparatus 100 comprises one or more of a magnetic, electrical, optical, biological, and atomic data storage media. In one example, the computer-readable signal-bearing media comprises a modulated carrier signal transmitted over a network comprising or coupled with the apparatus 100, for instance, one or more of a telephone network, a local area network ("LAN"), the internet, and a wireless network.

The steps or operations described herein are just exemplary. There may be many variations to these steps or operations without departing from the spirit of the invention. For instance, the steps may be performed in a differing order, or steps may be added, deleted, or modified.

Although exemplary implementations of the invention have been depicted and described in detail herein, it will be apparent to those skilled in the relevant art that various modifications, additions, substitutions, and the like can be made without departing from the spirit of the invention and these are therefore considered to be within the scope of the invention as defined in the following claims.